

Accuracy of 3D Virtual Planning of Corrective Osteotomies of the Distal Radius

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Abstract

Corrective osteotomies of the distal radius for symptomatic malunion are time-tested procedures that rely on accurate corrections. Patients with combined intra- and extra-articular malunions present a challenging deformity. Virtual planning and patient-specific instruments (PSIs) to transfer the planning into the operating room have been used both to simplify the surgery and to make it more accurate. This report focuses on the clinically achieved accuracy in four patients treated between 2008 and 2012 with virtual planning and PSIs for a combined intra- and extraarticular malunion of the distal radius. The accuracy of the correction is quantified by comparing the virtual three-dimensional (3D) planning model with the postoperative 3D bone model. For the extraarticular malunion the 3D volar tilt, 3D radial inclination and 3D ulnar variance are measured. The volar tilt is undercorrected in all cases with an average of $-6 \pm 6^\circ$. The average difference between the postoperative and planned 3D radial inclination was $-1 \pm 5^\circ$. The average difference between the postoperative and planned 3D ulnar variances is 0 ± 1 mm. For the evaluation of the intraarticular malunion, both the arc method of measurement and distance map measurement are used. The average postoperative maximum gap is 2.1 ± 0.9 mm. The average maximum postoperative step-off is 1.3 ± 0.4 mm. The average distance between the postoperative and planned articular surfaces is 1.1 ± 0.6 mm as determined in the distance map measurement. There is a tendency to achieve higher accuracy as experience builds up, both on the surgeon's side and on the design engineering side. We believe this technology holds the potential to achieve consistent accuracy of very complex corrections.

Keywords

- ▶ virtual planning
- ▶ patient specific instruments
- ▶ malunion
- ▶ osteotomy
- ▶ radius

In contrast to Colles's often quoted statement, not "every limb will at some remote period again enjoy perfect freedom in all its motions, and be completely exempt from pain."¹ In a retrospective study² on the major complications in a series of consecutive patients treated for Colles fracture, malposition-malunion was the most frequent reason for patient referral. Extraarticular malunions usually need correction of volar tilt and radial length.³ Intraarticular malunions present with an intraarticular step or gap, which frequently leads to posttraumatic arthritis.⁴ There is, however, no clear-cut correlation between the radiographic grading of the

posttraumatic arthritis and the impairment seen in the patient.⁵ Patients with symptomatic intra- and extraarticular distal radius malunions potentially need correction of the intra- and extraarticular malunion. These cases represent a significant technical challenge to the surgeon with respect to both the preoperative planning and the surgery.

Since the introduction of corrective osteotomy as the treatment of choice for both extra-⁶ and intraarticular⁷ malunions, we have come to realize that accuracy is important to achieve an optimal outcome.⁸ When the actual correction following an extraarticular osteotomy is compared with the

planned correction, only 40% of the corrections are within 5° of the desired correction of the angular deformity (volar tilt and radial inclination) and within 2 mm of the desired ulnar variance.⁹ The use of virtual planning in combination with patient-specific instruments (PSIs) has proven to be very accurate in mock operations on dry cadaver bone.¹⁰ PSIs are three-dimensional (3D)-printed as surface molds of the 3D bone model and have a unique fitting position onto the bone. Several functional elements are added to the PSI, including Kirchner wire (K-wire) holes to fix it to the bone, cylinders to be fitted with drill sleeves for drilling holes, and slits to perform osteotomies (►Fig. 1a–f). They are used during the surgery to transfer the treatment plan to the actual surgery (►Fig. 2a–b).

This article presents the clinically achieved accuracy of correction in four combined intra- and extraarticular osteot-

omy cases done for symptomatic distal radius malunion. All cases were treated using the same technique: virtual planning of the osteotomy, reverse engineering of the fixation screws, and surgery using PSIs. The accuracy of the reconstruction was determined by comparing the postoperative 3D computed tomography (CT) scan data with the virtually planned correction on the preoperative CT scan data.

Patients and Methods

We conducted a retrospective study on patients treated for combined intra- and extraarticular malunion of the distal radius in our service between 2008 and 2012 and identified four patients who were treated using preoperative virtual planning and PSIs during surgery (►Table 1). The average age

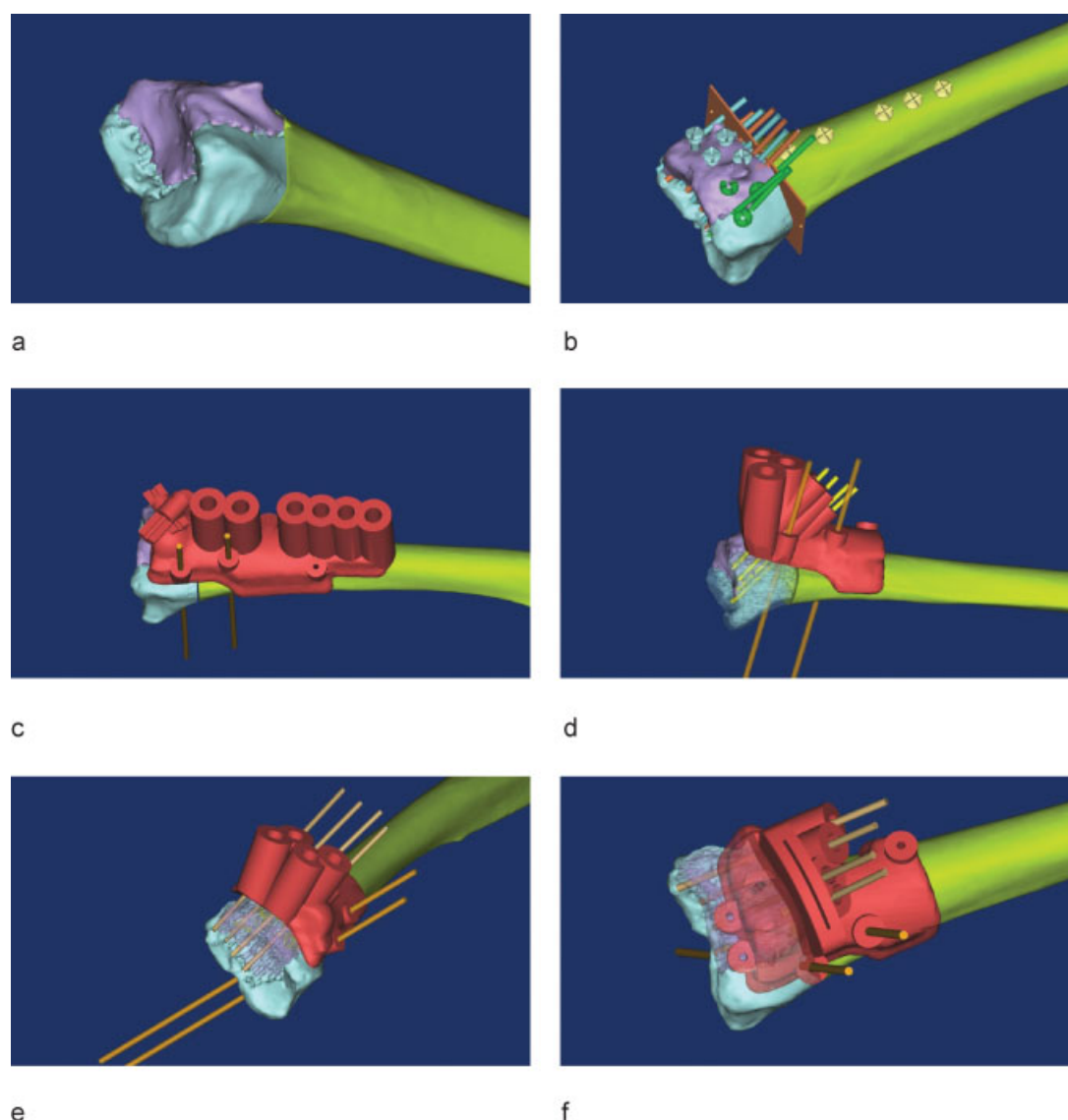


Fig. 1a–f Case example (KS). (a) Separation of the malunited radius into its element. (b) Position of the osteotomy plane, osteotomy drill holes, and reverse-engineered screw positions; colored per guide. (c) First PSI for shaft screws and two parallel K-wires, which will be used to position the consecutive guides. (d) Second PSI to predrill distal-ulnar screws (cylinders) and ulnar perforation holes (yellow). (e) Third PSI to predrill distal-radial screws (cylinders) and every other radial perforation holes (brown). (f) Fourth PSI to drill the remaining radial perforation holes (brown) and to guide the extra articular osteotomy (slot).

Table 1 Patient demographics

Patient	Age	Sex	Dominant hand	Profession	Initial treatment	Delay after fracture	Approach	Surgery date
1	66 yr	F	No	Housewife	Cast	6 mo	Dorsal	11/2008
2	62 yr	F	No	Housewife	Cast	6 mo	Volar	11/2009
3	60 yr	M	Yes	Dentist	Cast	7 mo	Volar	12/2010
4	28 yr	F	No	Chiropractor	Cast	16 mo	Dorsal	03/2011

at the time of surgery was 54 years (range 28–66 years); there were three female patients and one male, three of the treated wrists were nondominant and one dominant. All patients sustained an intraarticular fracture of the distal radius, initially treated with a cast. The major complaint was pain. The average time between the fracture and the corrective osteotomy was 9 months (6–16 months).

Virtual Planning and Surgical Technique

All patients were evaluated with bilateral preoperative CT scan (slice thickness: 0.625 mm). The segmentation of the radius and ulna was done in Mimics (Materialise, Leuven, Belgium); virtual planning was done using Surgicase (Materialise NV, Leuven, Belgium). During the virtual planning, the different parts of the malunion were isolated as individual structures. Correction of the extraarticular malunion was achieved by planning an osteotomy close to the original fracture site (point where the malunited radius starts to diverge from the mirrored, contralateral, unaffected radius). Treatment of the intraarticular malunion usually involved recreating the original fracture pattern with a series of 1–2-mm drill holes. The mirrored contralateral radius was used as a reduction template.¹¹ Once the reduction of the different elements was achieved, an electronic template of the implant, including its fixation screws, was used to optimize the planning. Once the final treatment plan is obtained, one can use this information (the end result) to define the necessary steps to turn the malunited radius and the corrected radius; this type of problem solving is also known as reverse engineering. In this case the positions of the fixation holes were reverse-engineered to find their position in the malunited position. The fixation device was used as a reduction tool in the final steps of the surgery. Once the planning was finalized, including the choice of the fixation device, the design process of the PSI was started. The PSI was used during surgery to transfer the virtually planned correction into the operating room. Combined intra- and extraarticular malunions require multiple consecutive PSIs (►Fig. 1a–f). Two of the K-wires used to stabilize the PSI on the radius were parallel and remained in place during the whole osteotomy process. The different PSIs were slipped into place over these parallel K-wires, thus maintaining the same spatial position of all PSIs onto the radius (►Fig. 2). The intraarticular osteotomy was performed first by drilling a series of 1-mm perforation holes along the original fracture line to weaken the bone structurally and facilitate recreating the original fracture. Thicker drill bits were needed to remove any excess

new bone. The subsequent PSIs were used to drill the reverse-engineered holes for the fixation screws. A PSI was then used to perform the extraarticular osteotomy. All PSIs were designed and produced by Materialise NV, Leuven, Belgium, using additive manufacturing. The complete process, segmentation, virtual planning, PSI design, and PSI production will take 6–8 weeks depending upon the complexity of the case. Fluoroscopy was used during surgery to control the PSI positioning and screw length, but it was not used to guide the reduction nor to alter the treatment plan.

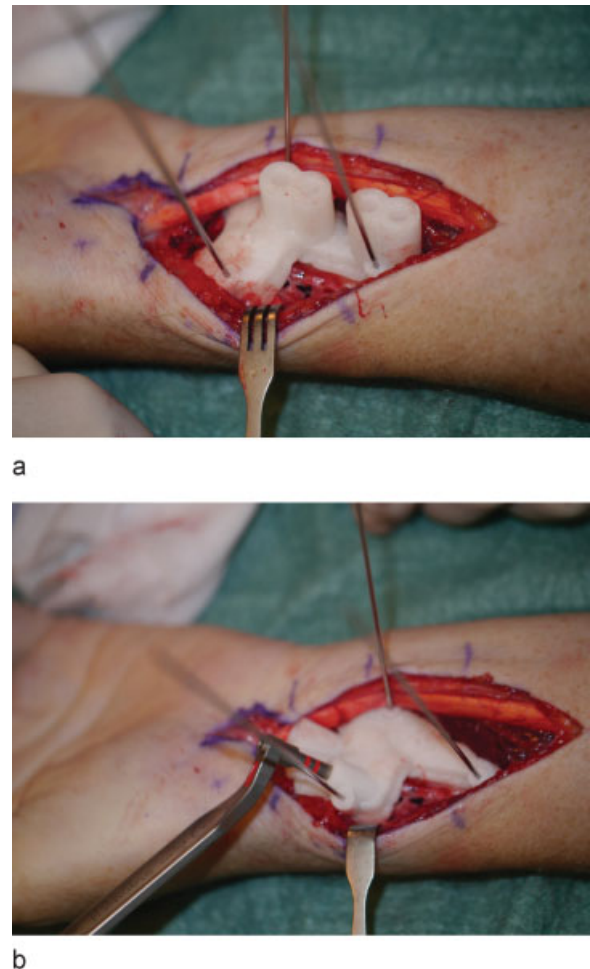


Fig. 2a–b Clinical example of two consecutive guides used to drill the shaft holes (a) and reverse engineered distal holes (b). The two K-wires on the foreground are parallel and are used to slip the second guide into place without removing them.

To evaluate the degree of postoperative correction, the Dicom images of a postoperative CT scan (slice thickness: 0.625 mm) of all patients were uploaded in Mimics (Materialise NV, Leuven, Belgium), and the radius was segmented out. 3D surface models were created, and the 3D models were uploaded in 3-Matic (Materialise NV, Leuven, Belgium) for further analysis (►Figs. 3a–d, 4a–d, 5a–d, 6a–d). For the evaluation of the extraarticular malunion correction, the 3D volar tilt and 3D radial inclination were measured using the 3D image of the radius postoperatively. To measure the 3D volar tilt, a reference point was marked on the volar and dorsal lip of the lunate fossa, adjacent to the sigmoid notch of the postoperative 3D radius, similar to the reference points used in lateral radiographs. To measure the radial inclination, the most distal point on the radial styloid was marked and the most proximal point on the rim of the lunate fossa adjacent to the sigmoid notch of the 3D radius was marked, similar to the reference points used in a posteroanterior (PA) radiograph. Next, the 3D surface models of the preoperative radius and the planned correction were uploaded into the same platform. The marked-out reference points for the measurements of the 3D volar tilt and 3D radial inclination were transferred from the postoperative 3D radius onto the planning model by using the bone surface of the postoperative model around the reference point for coregistration of the reference point itself. For the evaluation of the intraarticular malunion, the maximum step-off and gap were measured using the arc method of measurement¹² on the preoperative and postoperative CT scan slices. The arc method uses a circle to match the curvature of the articular surface on the CT scan image. The subchondral margin points were marked at the edge of each fragment, and a line was drawn from the center of the circle to these points. The point of intersection between the circle and the line that connects the center point with the

subchondral point of the displaced fragment was marked. The step-off is the distance between the crossing point and the subchondral point of the displaced fragment. The gap is the distance between the crossing point and the subchondral point of the nondisplaced fragment measured along the circle.¹² The average of three measurements was given. To have a more global measurement of the intraarticular alignment before and after correction of the malunion, a distance map measurement was generated between the articular surface positions of the planned corrections and their preoperative or postoperative positions. Since we focus here on intraarticular alignment, the articular surface of the fragment that is in continuity with the volar surface of the distal radius is used as reference region for the registration. The distance measurement is based on a closest-point algorithm. The results are expressed as average distance between the two surfaces \pm standard deviation and presented as a color-coded image map (►Fig. 7a–h).

Results

The extraarticular malunion was corrected by measuring the difference between the postoperative and planned 3D volar tilt, 3D radial inclination, and 3D ulnar variance (►Table 2). The volar tilt was undercorrected in all cases, with an average of $-6 \pm 6^\circ$. The average difference between the postoperative and planned 3D radial inclination was $-1 \pm 5^\circ$. The postoperative 3D ulnar variance was undercorrected in one case, and all other cases were slightly overcorrected; the average difference between the postoperative and planned correction is 0 ± 1 mm.

For the evaluation of the intraarticular malunion, the maximum postoperative gap and step-off are measured using the arc method of measurement (►Table 3). The average

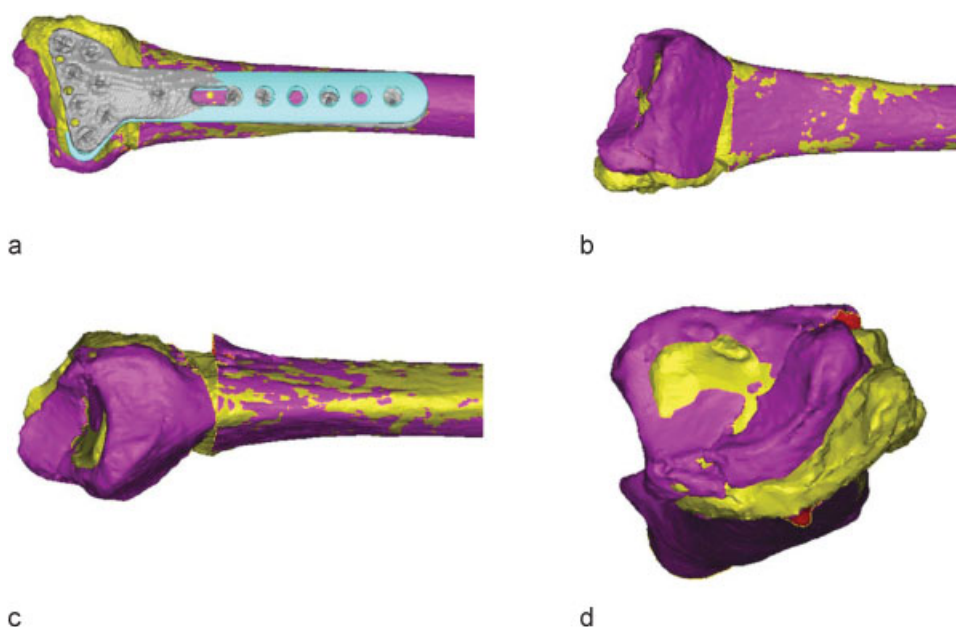


Fig. 3a–d Comparison between the planned correction (purple) and postoperative correction (yellow) of patient 1. (a) Dorsal view. (b) Volar view. (c) Ulnar view. (d) Axial view.

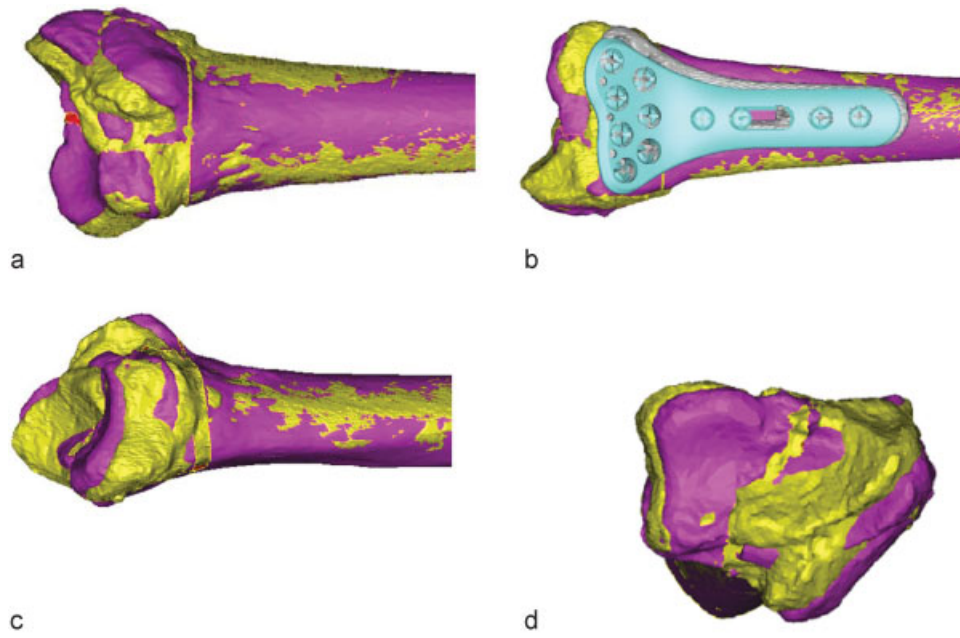


Fig. 4a–d Comparison between the planned correction (purple) and postoperative correction (yellow) of patient 2. (a) Dorsal view. (b) volar view. (c) Ulnar view. (d) Axial view.

postoperative maximum gap is 2.1 ± 0.9 mm. The average maximum postoperative step-off was 1.3 ± 0.4 mm. The average distance between the postoperative and planned articular surfaces was 1.1 ± 0.6 mm. This value only quantifies the quality of the intraarticular correction. When the distance maps were compared with the results of the maximum residual step-off, the alignment was best achieved around the fracture line, and most of the deviation from

the planning was seen at the edges of the articular surface (**►Fig. 7a–h**).

Discussion

This technology was first used in our department in 2005 for virtual planning of a Madelung corrective osteotomy without the use of PSIs. PSIs were introduced in 2007 with our first

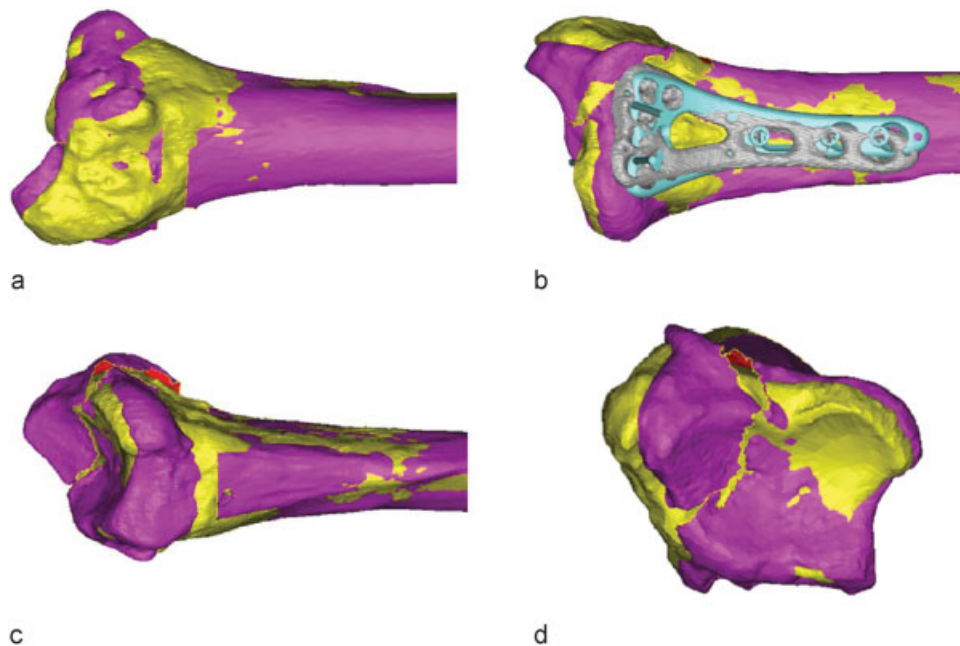


Fig. 5a–d Comparison between the planned correction (purple) and postoperative correction (yellow) of patient 3. (a) Dorsal view. (b) volar view. (c) Ulnar view. (d) Axial view.

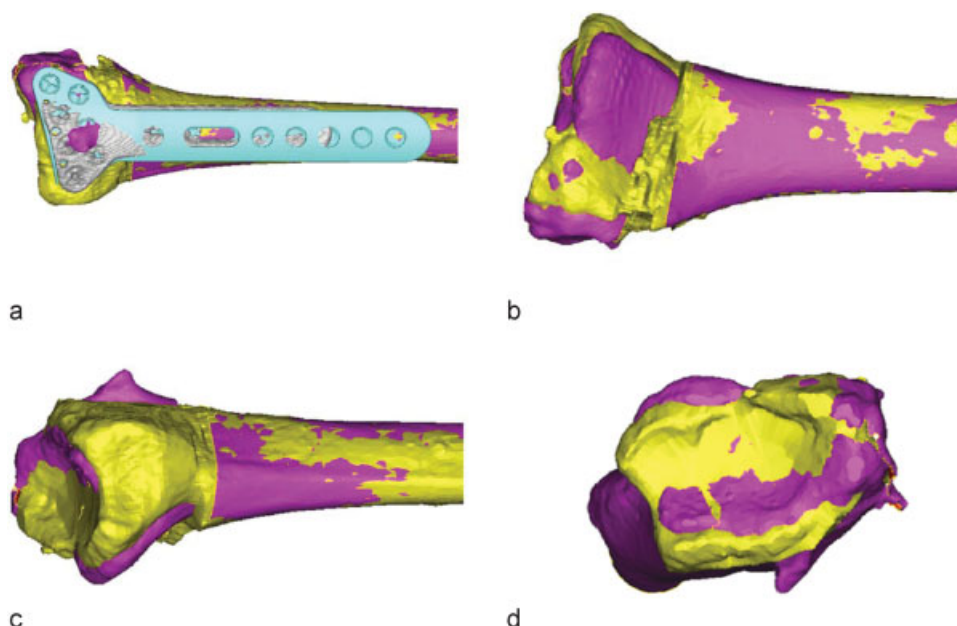


Fig. 6a–d Comparison between the planned correction (purple) and postoperative correction (yellow) of patient 4. (a) Dorsal view. (b) volar view. (c) Ulnar view. (d) Axial view.

intraarticular malunion of the radius. Since then, 35 distal radius cases of different nature have been performed with this technology in our service, only four of whom needed a combined intra- and extraarticular correction of the radius. The goal of corrective osteotomies is to reconstruct the anatomy with high precision. In combined intra- and extraarticular corrections, it is difficult to rely only on tracing paper, clinical judgment, and 2D fluoroscopy. Various solutions have been suggested, ranging from arthrotomy⁷ and arthroscopy with inside-out osteotomy¹³ to experimental navigation¹⁴ and PSIs produced using additive manufacturing. Arthrotomy is the most obvious way to go when dealing with a limited, severe intraarticular malunion. The main shortcoming of this technique is the limitation in exposing the radiocarpal and distal radioulnar joint surface without destroying its ligamentous support. Arthroscopy does offer an attractive alternative for the limitations of the open technique. Separating the different fragments can be achieved by inside-out osteotomy with curved osteotomes.¹³ This can be achieved only in relatively fresh fractures. Once mature callus is obtained, it becomes even more difficult to do the inside-out osteotomy, which is already difficult because of space limitations in the radiocarpal joint.

As reported previously, the presurgical planning alone of complex osteotomies on 3D models offers multiple advantages.¹⁵ The surgeon not only gains more insight in the complexity of the deformity but also can fine-tune the operation and evaluate the feasibility of the intended procedure. Soon after the possibilities of virtual surgery planning were reported, it came to be preferred over planning on 3D physical models.¹⁶ The different virtual trials are done at no additional cost, which contrasts with trial surgery on physical models, which as a rule can be performed only once. Another advantage of virtual planning is the possibility to bring the planning into

the operating theater by uploading the project into navigation software. The problem, however, in the upper extremity is the use of tracking markers and instruments, because of size-limiting factors. The use of PSIs can be seen as an alternative for navigation. It avoids the use of intraoperative computer technology and becomes time-reducing when used instead of time-consuming as is the case with computer navigation.¹⁷ The PSI technology has been used for many years in dental implants,^{18,19} and more recently it was introduced in the orthopedic field for knee arthroplasty.²⁰ PSIs serve as an intraoperative navigation tool to perform surgical functions with high precision. The surgical accuracy of the PSI depends mostly upon the unique fitting and the stability of that fit onto the surface of the affected bone; therefore, PSI design is of key importance in achieving accurate corrections.²¹ The incorporation of the fixation device into the planning process allows assembly of the different fragments using the fixation device as if it were the last PSI to be used.

When we compare accuracy of our results with published results, some nuances should be made. The previously reported accuracy of PSI used on dry cadaver bones evaluated only extraarticular osteotomies. In actual surgery the placement of the PSI onto the bone usually necessitates a somewhat wider exposure of the bone surface. In most cases the soft tissue envelope will block the vision in double-checking for the optimal PSI fit. It is therefore not surprising that accuracy measurements on dry cadaver bone are more representative for evaluating the technological limits of the system than for the realistic clinical accuracy. When the published clinical results of corrective osteotomies are taken as benchmark to evaluate the achieved accuracy, we see that volar tilt was a more difficult correction to achieve than radial inclination and ulnar variance. The intraarticular correction could be achieved in all cases with a maximum residual step-

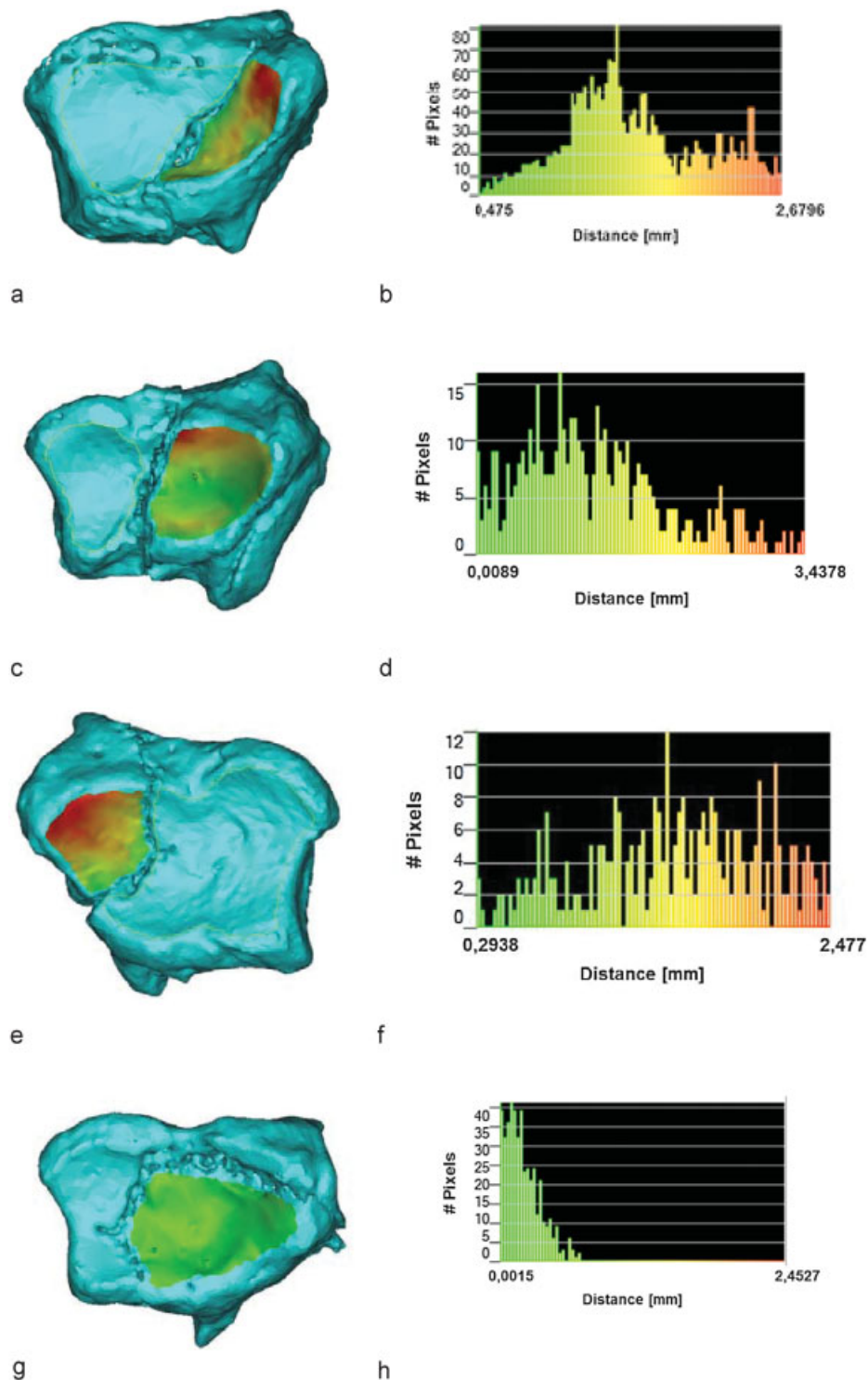


Fig. 7a–h Color coded distance map of the achieved intra-articular correction and corresponding histogram: case 1 (a,b), case 2 (c,d), case 3 (e,f) and case 4 (g,h).

off below 2 mm. There is, however, a tendency to under-correction of the fragment orientation, which hinges around the intraarticular osteotomy line. Although it is acknowledged that conventional surgical skills and peroperative fluoroscopy are sufficient in many cases, more complex cases—such as combined intra- and extraarticular osteotomies with combined angular, length, and rotational reconstruction—most certainly are facilitated by the use of this

technology. The preliminary results of the prospective randomized trial for extraarticular distal radius osteotomies comparing conventional planning with virtual planning and PSIs²² will be available in 2014. The achieved accuracy increases with the buildup of experience, probably on both the surgeon's side and the design engineering side. A close collaboration between the engineer responsible for the PSI design and the surgeon is mandatory. This technology does

Table 2 Evaluation of extraarticular correction (measurements done in 3D)

Patient	3D Volar tilt (°)			3D Radial inclination (°)			3D Ulnar variance (mm)	
	Planned	Postop	Δ	Planned	Postop	Δ	Postop	Δ
1	9	-1	-10	26	21	-5	-5.4	-0.6
2	15	7	-8	17	23	6	0	1.7
3	5	-3	8	22	19	-3	-2.0	-0.5
4	11	14	3	19	19	0	-0.6	-0.6
Av \pm Std	10 \pm 4	4 \pm 8	-6 \pm 6	21 \pm 4	21 \pm 2	-1 \pm 5	-2 \pm 2	0 \pm 1

Table 3 Evaluation of intraarticular malunion and its correction

Patient	Maximum gap (mm)		Maximum step-off (mm)		Average distance between surfaces (mm)	
	Preop	Postop	Preop	Postop	Preop versus Planning	Postop versus Planning
1	3.9	1.3	2.1	1.5	1.9 \pm 0.5	1.5 \pm 0.5
2	1.9	3.2	3.1	1.6	1.4 \pm 0.5	1.1 \pm 0.7
3	2.1	2.5	2.0	1.5	1.1 \pm 0.4	1.4 \pm 0.6
4	2.3	1.4	1.1	0.7	0.6 \pm 0.3	0.2 \pm 0.3
Av \pm Std	2.6 \pm 0.9	2.1 \pm 0.9	2.1 \pm 0.8	1.3 \pm 0.4	1.3 \pm 0.5	1.1 \pm 0.6

hold the potential to achieve consistent accuracy of very complex corrections. It offers the possibility to correct complex cases that would be treated conservatively otherwise because the surgeon would not be willing to take the surgical risk without precise preoperative planning and intraoperative guidance.

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Conflict of Interest

None

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